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THESIS

HELICOPTER VERTICAL STABILIZER
DESIGN CONSIDERATIONS

by

James E. Young

June 1983

Thesis Advisor: Donald M. Layton

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T208976

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Helicopter Vertical Stabilizer Design Considerations		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis June 1983
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) James E. Young		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE June 1983
		13. NUMBER OF PAGES 58
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Helicopter
Stabilizer
Anti-torque

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Helicopter Vertical Stabilizer
Design Considerations

by

James E. Young
Captain, United States Army
B.S., United States Military Academy, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1983

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ABSTRACT

Helicopter vertical stabilizer design considerations are receiving increasing emphasis from the helicopter community. Recent development programs experienced problems with respect to the empennage. Naval Postgraduate School Helicopter Design Course sophistication demands inclusion of vertical stabilizer parameters. The parameters are addressed in terms of conventional airfoil design considerations such as airfoil section, planform area, aspect ratio, camber, and sweep back angle. Specific to helicopters is the relationship to the tail rotor. The fundamental design tradeoff is maximum vertical stabilizer size to optimize directional stability and flight with zero tail rotor thrust contrasted to minimum size to optimize tail rotor blockage effects. A conceptual design procedure is developed herein.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENT

The contribution of Robert P. Smith, Applied Technology Laboratory, USAAVRADCOM, is most gratefully acknowledged. The primary references used in the writing of this thesis were provided by him. He contributed considerable time and effort by assuming a prominent role in the education process inherent in the thesis evolution. A significant portion of the knowledge gained during the course of this writing was a direct result of his interest and concern.

I. INTRODUCTION

A. BACKGROUND

Single rotor helicopters with fuselage mounted engines develop a fuselage torque equal and opposite to the main rotor torque. This necessitates an anti-torque device, mechanism or method to counteract main rotor torque. Currently, the standard for such devices consists of a tail mounted rotor system. The horizontal nature of the tail rotor thrust dictates a vertical (or nearly so) mounting configuration. Requirements for clearance between the tail rotor and the ground and between the tail rotor and the main rotor usually beget a vertical structure called the vertical stabilizer. (Main rotor/tail rotor synchronization is generally considered unfeasible and will not be discussed herein) [Ref. 1]. Functions performed by the vertical stabilizer vary to some extent from helicopter to helicopter and include one or more of the following:

1. Streamlining the tail rotor support;
2. Augmenting the directional stability produced by the tail rotor;
3. Unloading the tail rotor in forward flight by providing some antitorque force;
4. Supporting a T-tail horizontal stabilizer;
5. Providing directional stability in the event of a complete loss of the tail rotor [Ref. 2].

Several light helicopters such as the Hughes 500/OH-6, Bell 206/OH-58, Aerospatiale AS-350 A Star, and the Augusta 109A are configured with vertical stabilizers but have their tail rotor assemblies mounted on the tail boom as opposed to the vertical stabilizer. The small tail rotor with its corresponding minimal ground clearance requirement facilitates this configuration. [Ref. 2]

Simply stated, the trade-offs to be considered in vertical stabilizer design are, the greater the area of the vertical stabilizer the more the directional stability is enhanced but the greater the adverse effects on tail rotor efficiency due to the vertical stabilizer blockage of air flowing either to or from the tail rotor, depending on configuration. Also demanding consideration are the weight and balance effects, both static and dynamic, of any empennage structure (tail rotor, horizontal and vertical stabilizers). These effects are compounded due to empennage remoteness from the center of gravity.

A fair amount of published material is available pertaining to the tail rotor, however, such is decidedly not the case with respect to the empennage or the vertical stabilizer. The predominant reason for this situation may be a lack of detailed understanding inasmuch as the empennage exists in an extremely complicated flow environment. To be considered is the main rotor wake impingement on the

vertical stabilizer, tail rotor flow impingement on the vertical stabilizer, and main rotor and tail rotor interactions and their effects on the vertical stabilizer. Once these three flows are understood individually, the combined effects require attention.

Flow impingement on the empennage is further complicated by the presence and effects of various vortices. Contributing are main rotor trailing vortices, the vortex ring shed from the tail rotor, and the ground vortex formed as a result of the meeting of main rotor trailing vortices and the relative wind. Further compounding the situation is an unequal empennage dynamic pressure as a result of dissimilar advancing and retreating blade main rotor wake.

This is certainly not to say that the situation is hopeless. But, the lack of correlation of theoretical and experimental results renders definitive theories and statements subject to valid criticism. It is also responsible for the fact that presently much helicopter design work is, to a considerable extent, accomplished by trial and error experimentation. Engineers and designers are unable to provide explanations in terms of exact science. Incredulous as it may seem to many engineers, there is considerably more truth than falsehood to the statement that helicopter design engineering is an inexact science. Not surprisingly, there is a lack of agreement throughout the industry. Different

manufacturers and engineers cite diverse reasons and explanations for various practices and designs. The issue of tail rotor direction provides an example. Three different reasons have been stated as the reason why tail rotors should always rotate with the top blade moving aft.

Another point is the lack of uniformity of nomenclature with respect to this part of a helicopter. The helicopter community does not even agree on what to call the vertical stabilizer. Bell-Textron uses 'vertical fin', Sikorsky prefers 'vertical tail', Hughes likes 'vertical stabilizer', Boeing-Vertol chooses simply 'fin', and 'vertical pylon' or 'tail rotor pylon' has some supporters. No fewer than eight persons from various organizations, government and civilian, have acknowledged Mr. Raymond Prouty, of Hughes Helicopters Inc., as the "expert" on this subject. He terms the item the 'vertical stabilizer' and this term will be used in this report.

Design considerations for the vertical stabilizer have recently begun receiving considerable attention from the helicopter community. Two of the most recently developed helicopters are the U.S. Army/Hughes AH-64 Apache and the U.S. Army/Sikorsky UH-60A Blackhawk. Both of these programs encountered considerable empennage problems at various design and production stages. Efforts toward understanding and solving these problems have been documented in

References 1, 3, and 4 and serve as part of a design data base. Purposes of this documentation are threefold:

1. Summarize the problems, experiences and data associated with empennage design;
2. To expand the technical data base of current helicopter design;
3. To develop limited design criteria and guidelines for use in the development of future helicopters. [Ref. 5]

Current operational Army helicopters such as the OH-58/Bell 206 and the AH-1/Bell Cobra have exhibited directional stability problems throughout various stages of their life cycles. The AH-1 Cobra underwent major modifications to include alteration of the tail rotor from a pusher configuration (tail rotor mounted on the left side of the vertical stabilizer such that the rotor wake does not strike the vertical stabilizer) to a tractor or puller configuration (tail rotor mounted on the right side of the vertical stabilizer such that the rotor wake strikes the vertical stabilizer). The next iteration involved adding a pronounced camber to the vertical stabilizer.

Vertical stabilizer design factors have heretofore not been considered in the Naval Postgraduate School Helicopter Design Course. Course sophistication has progressed to a point where such consideration is now feasible. Helicopter

design computer programs previously developed and utilized at the Naval Postgraduate School have not included vertical stabilizer unloading of the tail rotor in forward flight.

Inasmuch as the vertical stabilizer operates as an integral component of the empennage in a complex environment, consummate academic treatment should provide analysis of the empennage as an entity including the relationships of the three empennage components and the myriad of factors which influence them. Understandably, such an endeavor would constitute a monumental undertaking. This thesis intends to be narrow in scope and to include design considerations pertinent to the vertical stabilizer, independent of the empennage with exception to some analysis with respect to the tail rotor. Appreciation for the relationship between the vertical stabilizer and the tail rotor is paramount to an understanding of the subject of this thesis. The effort is also restricted to the "classical" helicopter without regard for current innovative concepts. The classical helicopter is of medium weight (maximum gross weight of 9,000 to 20,000 pounds) and configured with a low tail necessitating a vertical stabilizer to provide support and ground clearance for a conventional tail rotor assembly.

B. GOALS

1. Development of an understanding of helicopter vertical stabilizer design considerations is imperative. Such considerations as airfoil section, planform area, aspect ratio, camber, sweep back angles and relationship to the tail rotor are of interest.

2. Integration of the above-mentioned design considerations into the Naval Postgraduate School Helicopter Design Course will greatly enhance the degree of sophistication attained by that course.

3. Quantification of inflight vertical stabilizer caused tail rotor loading effects permits modification of Naval Postgraudate School helicopter computer programs. This degree of refinement will greatly increase the accuracy of these programs.

II. DESIGN PARAMETERS

A. INTRODUCTION

As previously stated, the fundamental tradeoff in vertical stabilizer design is to maximize vertical stabilizer size, which dictates aircraft performance and controllability in the event of loss of tail rotor thrust, while also maximizing tail rotor thrust which provides directional stability. Unfortunately, the relationship is inverse as the two concerns are in decided opposition to each other. There exists no simple 'cookbook' optimization procedure yielding a definite solution. The complex interactional aspects of the main rotor, tail rotor and vertical stabilizer regarding their flows and placements with respect to each other render such a solution nearly incomprehensible from an analytical standpoint.

The endeavor here is to present design parameters in the sense that any airfoil might be analyzed: planform area, sweep angles, airfoil section type, aspect ratio and camber. The most fundamental and critical is the relationship to the tail rotor, as this directly affects the remaining parameters. Inherent in the tail rotor analysis is discussion of the spacing ratio (s/r) which is defined as the ratio of the distance between the vertical stabilizer and

the tail rotor hub to the tail rotor radius. A typical value for this parameter is 0.45 [Ref. 6].

B. TAIL ROTOR RELATIONSHIP

Interposing the vertical stabilizer into the flow field of a pusher tail rotor results in adverse fin loads and an increase in tail rotor power required. In producing thrust, the tail rotor causes airflow along the surface of the vertical stabilizer. As airflow over an airfoil is inclined to do, a pressure differential is created on the stabilizer and tail boom on the tail rotor side of the stabilizer. This pressure differential integrated over the surface yields a lift or thrust force which opposes tail rotor thrust and, thus, must be subtracted from the tail rotor shaft thrust to obtain an effective net tail rotor thrust. In addition, the vertical stabilizer's presence on the inflow side of the tail rotor results in distortions of the flow distribution across the tail rotor disk resulting in further increased tail rotor power requirements. [Ref. 7]

These two effects are considered in combination as the blockage of the tail rotor by the vertical stabilizer. The blockage ratio becomes a major design variable and is defined as the ratio of that portion of the stabilizer area which the tail rotor overlaps to the total tail rotor disk area [Ref. 6]. Typical blockage ratios vary from 25% to 35%

traditionally to values as high as 50% in newer designs. Figure 1 indicates the relative difference between a 25% and a 35% vertical stabilizer.

Adverse stabilizer forces are primarily a function of thrust, stabilizer size and shape, and spacing ratio. There is also a sensitivity to relative wind velocity and to main rotor wake. Flight tests have shown pusher configured tail rotors to be especially sensitive to wind direction. A wind direction from the left increases the stabilizer force over that of a no wind environment. The area of greater adverse pressure is also seen to propagate forward along the tail boom thereby further decreasing net thrust. The tractor configuration with a top blade aft direction of rotation has proven relatively free of wind effects although these benefits are offset by higher stabilizer sideload losses. Extensive test data is presented in Reference 6. A caution is warranted that such test data may be configuration dependent to a large extent [Ref. 8].

The spacing ratio (s/r), distance between hub and stabilizer to tail rotor radius, is inversely related to both the adverse stabilizer force and the tail rotor shaft thrust. As the spacing ratio decreases, stabilizer force and shaft thrust both increase resulting in a constant net thrust. A low spacing ratio configuration stalls at a lower net thrust. Thus, for equal stall characteristic tail

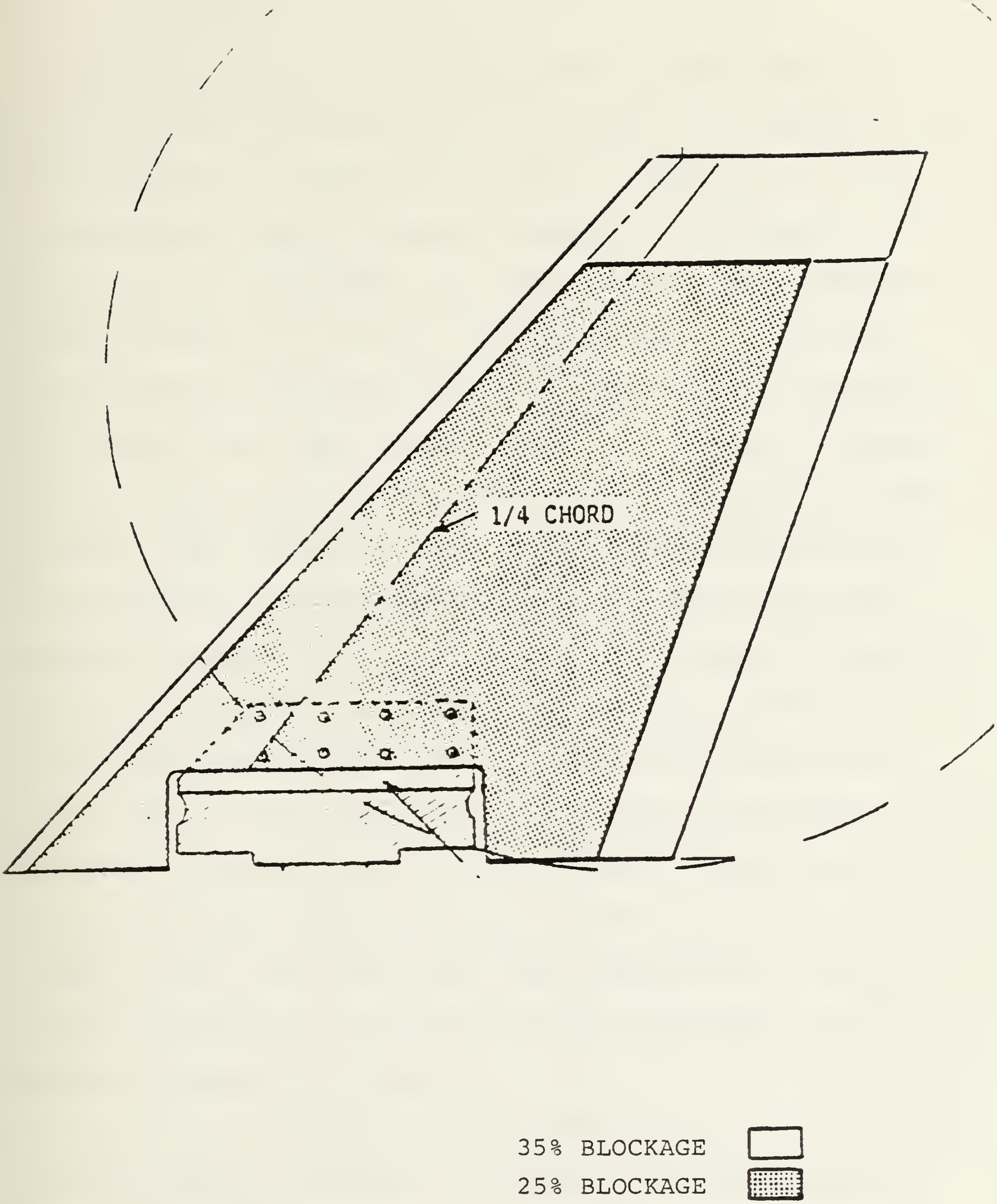


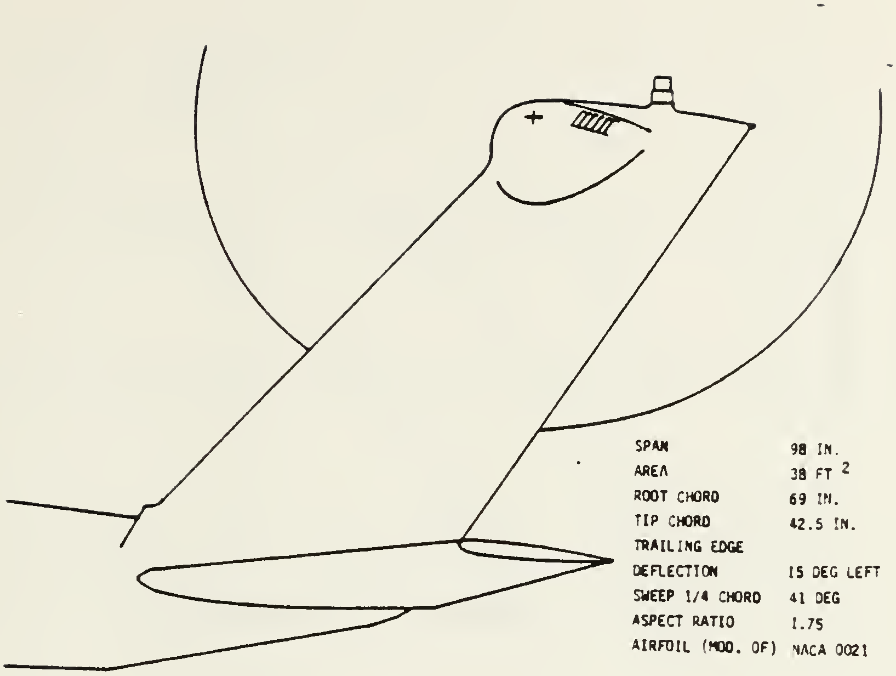
FIGURE 1 INTERCHANGEABLE VERTICAL FIN

rotors, a greater spacing ratio permits lower tail rotor disk solidity. Spacing ratio is treated as a primary design characteristic in References 6 and 8. However, it was not considered as such by Hughes during AH-64 development. The criticality of empennage components due to their remoteness from the center of gravity was pointed out by Mr. Prouty when discussing the feasibility and advisability of varying the spacing ratio as a design parameter. Doing so can have far-reaching impact on aircraft dynamics and on weight and balance. His belief was that spacing ratio should not be considered as a design variable or, at least, should be employed as such as a last resort. The designer or engineer must be incessantly cognizant of the nature of the tail rotor's rotational velocity (4-6 times that of the main rotor) and of the inherently narrow weight and balance limitations of the helicopter. Mr. Prouty also mentioned the fact that Hughes possessed a drive shaft which was a proven component and with which they were comfortable. Use of proven components is perhaps an often overlooked aspect of engineering design. [Ref. 9]

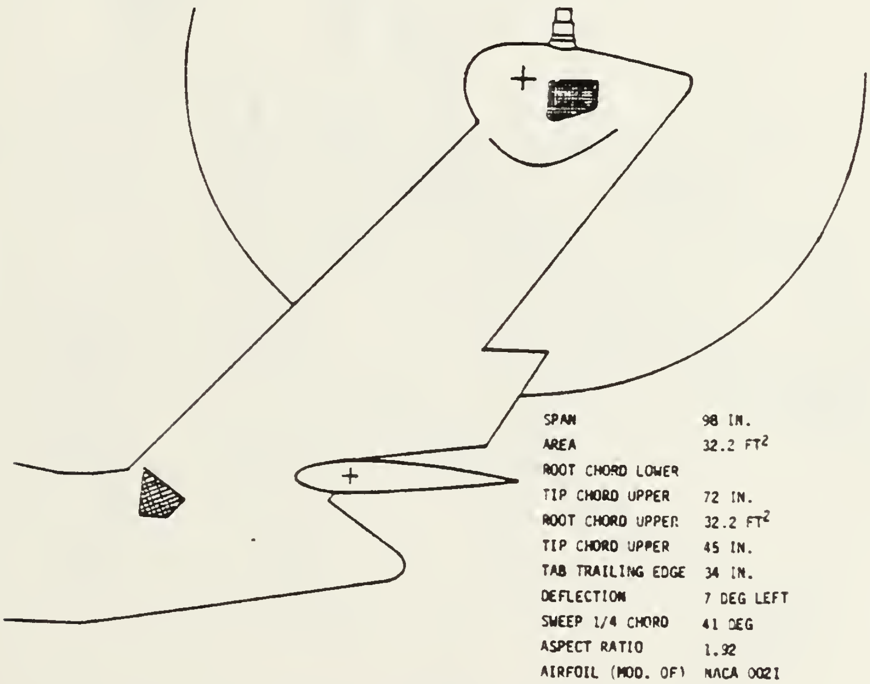
Tail rotor placement with respect to the stabilizer can be a key design variable. The stabilizer influences main rotor tip and ground vortices effects on the tail rotor. The blockage ratio and adverse stabilizer forces are directly related to the tail rotor position. Tail rotor

placement studies, with variations in longitudinal, lateral and vertical positioning are presented in Reference 3. Figures 2 and 3 show tail rotor, vertical stabilizer placements for the UH-60 and AH-64. A comprehensive description of tail rotor placement and effects can be found in Reference 3.

Several additional tail rotor parameters merit mention. Tail rotor shaft sweep angle variations can prove effective. A forward sweep of 5 degrees seems a near optimum amount. Quantitative analysis indicates that a bottom forward/top aft direction of rotation is optimum for helicopter tail rotors. This factor is independent of configuration (tractor or pusher) [Ref. 6]. Authorial supposition here is that the leading edge of the tail rotor deals more efficiently with the main rotor wake than the trailing edge. Some documentation was discovered which precipitated this supposition although no unequivocal qualitative analysis relating cause and effect could be located. Reference 6 presents a fairly extensive amount of quantitative experimental evidence in verification. Mr. Prouty commented that noise was also a viable consideration here, in that the leading edge moving up into the main rotor wake produced considerably less noise than the converse. Interference effects between the tail rotor and the stabilizer appear to become significant when the chord of the vertical stabilizer



a) Initial YUH-60A Vertical Tail



b) Final UH-60A Vertical Tail

Figure 2 Vertical Tail Description.

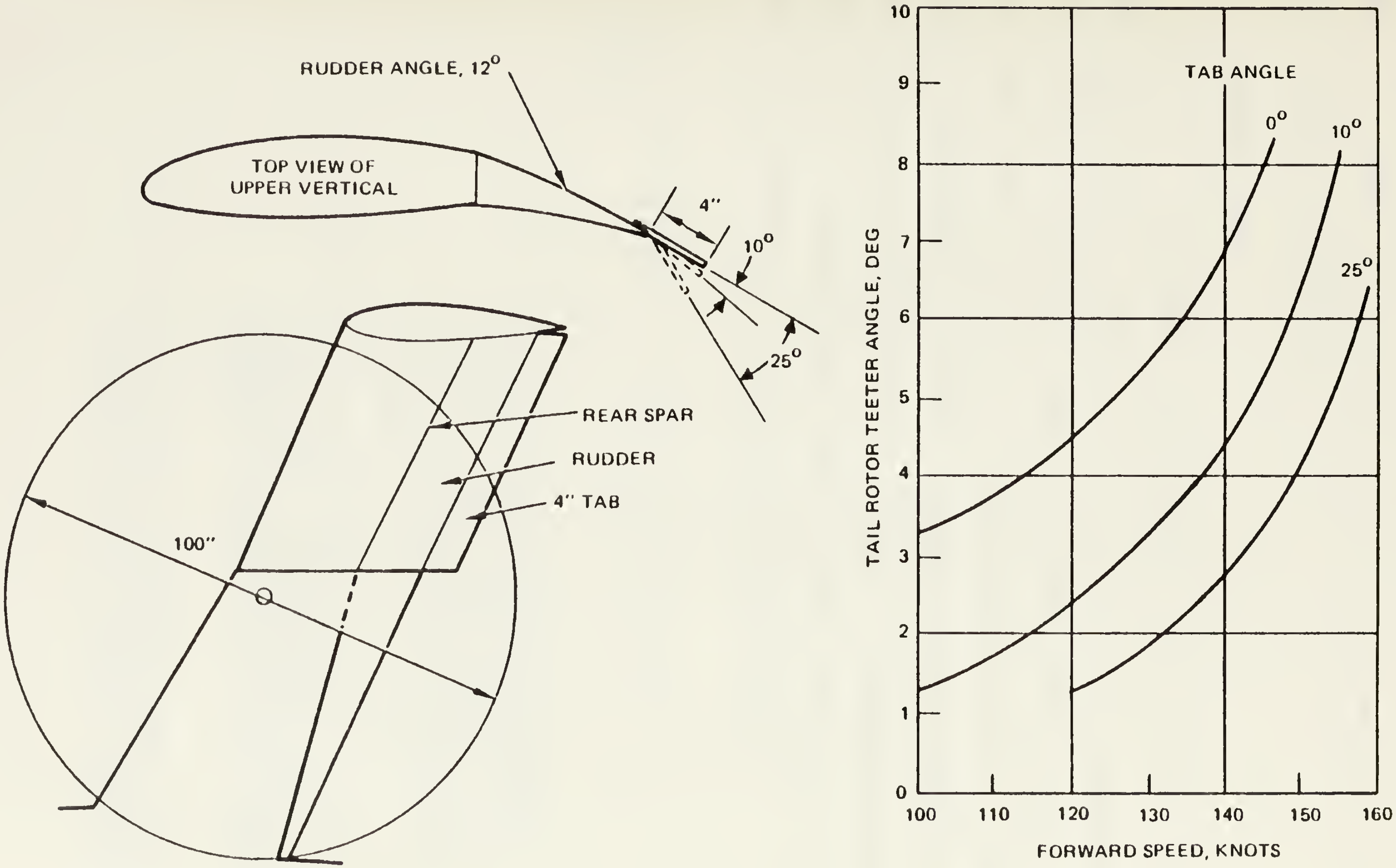


Figure 3 Effect of Tab Angle on Tail Rotor Teetering With T-Tail

approaches or exceeds one-half of the tail rotor radius. [Ref. 10] This is generally the case for medium or greater gross weight helicopters.

C. PLANFORM AREA

While no "cookbook" method exists for initial vertical stabilizer design, new helicopter designs and specifications giving high priority to zero tail rotor thrust flight produces one method as to how initial sizing might be conducted. Designing to achieve neutral static stability at zero tail rotor thrust flight insures a positive static stability in normal flight with the tail rotor on. The following procedure is adapted from Reference 1.

$$S_{vs} = d(N/q)/d(\psi) \;\; / \;\; Cl\alpha \times l_t \times (q_{vs}/q)$$

where:

$d(N/q)/d(\psi)$ = tail off fuselage yawing moment coefficient Determined from Figure 4 with some initial knowledge with respect to the profile area indicated at the top of Figure 4.

$cl\alpha$ = lift curve slope of the vertical stabilizer. Determined from Figure 5. See discussion herein regarding aspect ratio and sweep angles.

l_t = tail length, measured from the center of gravity to the assumed center of pressure of the vertical stabilizer

q_{vs}/q = dynamic pressure ratio at the vertical stabilizer Typical values are 0.6 to 0.75. A function of how clean the flow can be expected to be at the tail--designer assumption in the initial design phase. Figure 6 gives typical q_{vs}/q values as a function of sideslip.

This method neglects sidewash angle corrections and vertical stabilizer effect on yawing moment. These are small and can easily be neglected during initial design.

Detail sizing will depend greatly on specification requirements. If flight without tail rotor thrust receives high priority, a vertical stabilizer area permitting flight at maximum gross weight, at best range velocity, with zero tail rotor thrust, and a rate of climb of at least 100 fpm might be reasonable. However, as recent experience indicates, such an area may result in a prohibitive blockage ratio. [Ref. 1]

D. SWEEP ANGLES

Vertical stabilizer sweep angles can be derived from DATCOM (4.1.3.2), [Ref. 11], provided some data is known (or an assumption made) pertaining to aspect ratio, tip chord-root chord ratio, or span. One must begin somewhere. Analysis indicates that permitting geometric factors to determine the leading edge sweep angle is quite reasonable and, in fact, is probably the case more often than not. For

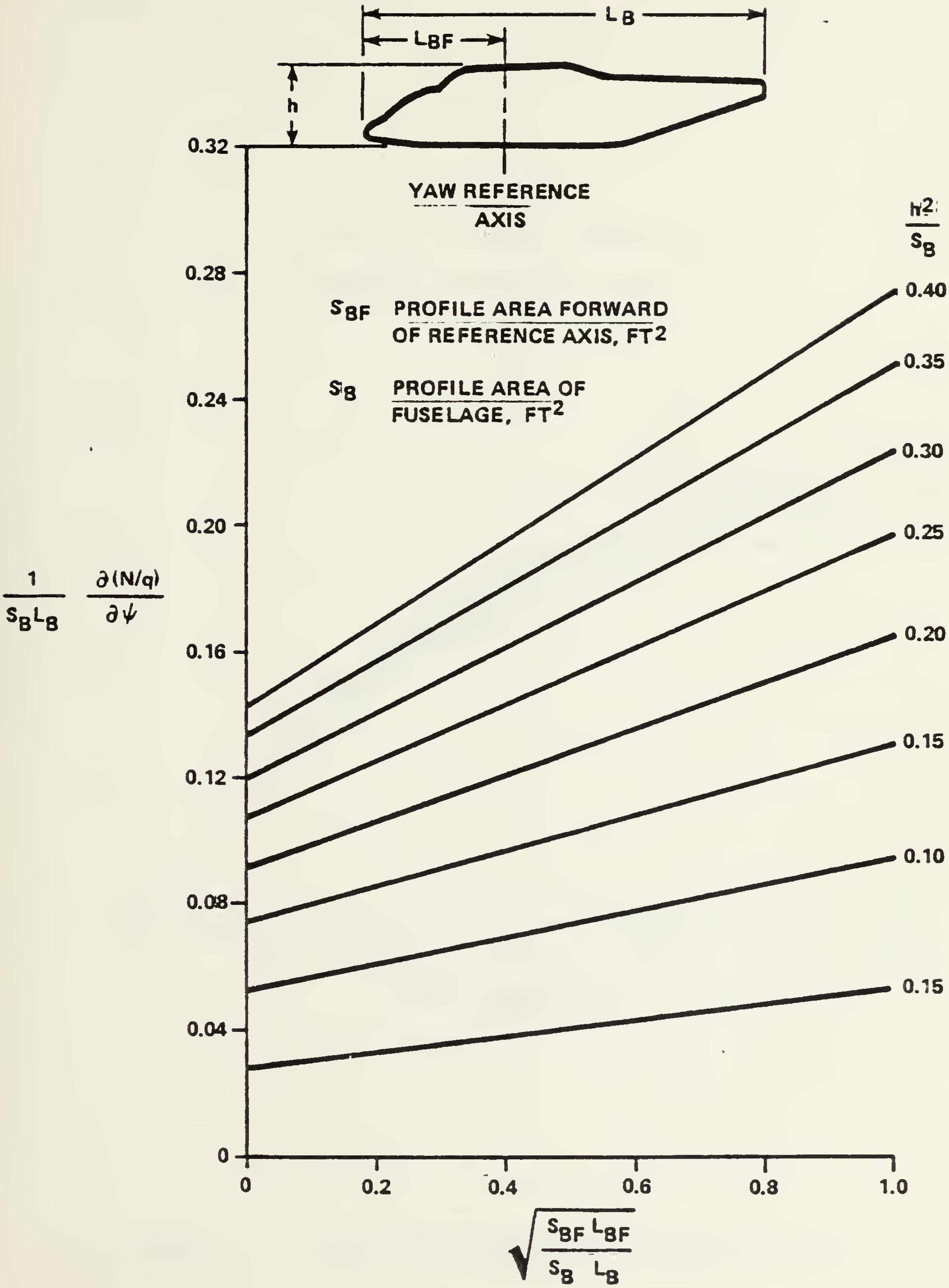


Figure 4 Fuselage Moment Parameter Slope.

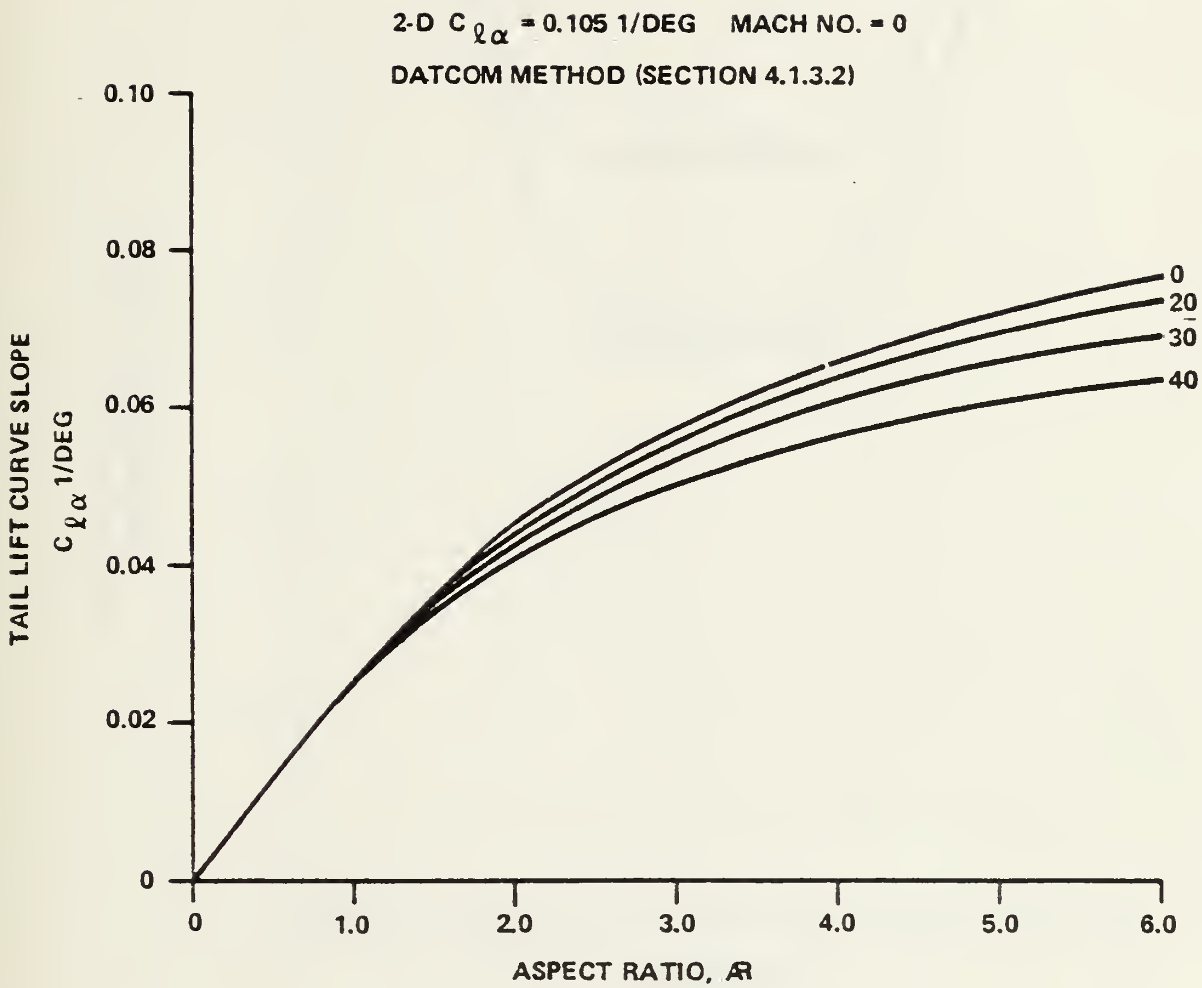


Figure 5 Lift Curve Slope vs Aspect Ratio.

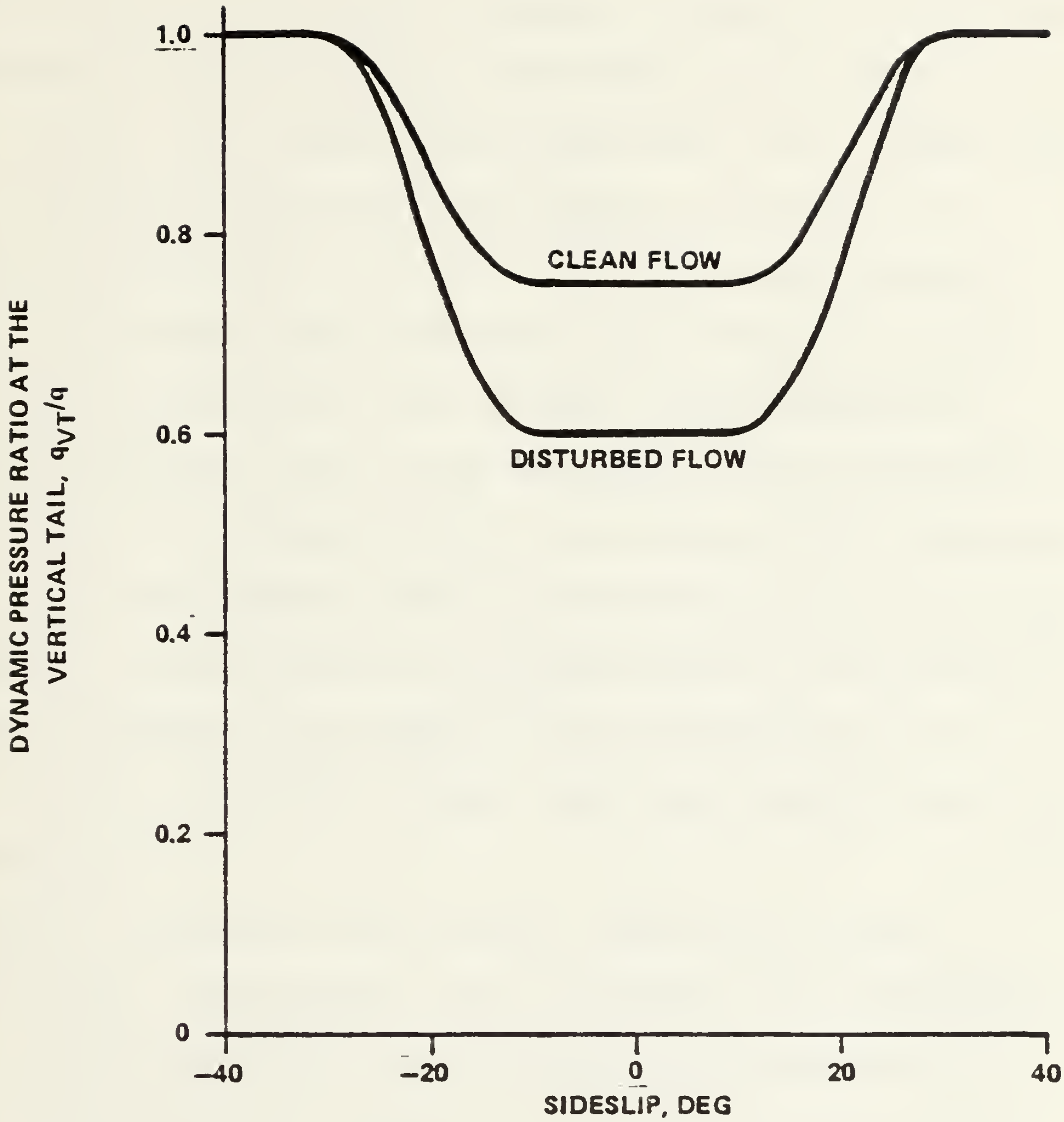


Figure 6 Typical Helicopter Dynamic Pressure Ratio at the Vertical Tail.

medium weight helicopters a leading edge sweep angle near 40 degrees is good. See Table I. Main rotor and tail rotor radius should be known by the time the vertical stabilizer is considered in the design sequence. Adding 0.5 feet (for clearance) to the sum of the main rotor radius and the tail rotor radius, the leading edge sweep angle then becomes that which would minimize weight and moment effects due to empennage components. As such, the sweep angle becomes a function of gross weight and power required as the rotor radii are a function of those primary design parameters.

An interesting note is the fact that a Bell Helicopter representative indicated that in the design of the venerable UH-1 series helicopters, the fact that there was an existing 42 degree intermediate tail rotor gear box on the shelf as a proven component was thought to be contributory to the UH-1 vertical stabilizer leading edge sweep angle which is 42 degrees.

Table I presents some vertical stabilizer airfoil section data. References 1 and 4 indicate that performance was a primary consideration in airfoil selection for the UH-60 and the AH-64. Certainly structural considerations are important also. The thickness must be such that the vertical portion of the tail rotor drive shaft is enclosed and supported and provides the requisite clearance. It should also be noted that the vertical stabilizer provides

the only support for the tail rotor and tail rotor gearbox which produce considerable moments due to their remoteness from the center of gravity and their not insignificant weights.

The UH-1 airfoil section is indicated as NACA 0015 [Ref. 12], and declared as such in Table I. Bell reported that the Huey's vertical stabilizer did not correspond to a specific airfoil section type [Ref. 13]. U.S. Army testing specifications indicate that the Huey stabilizer is indeed the NACA 0015 [Ref. 12]. One might suppose that the Huey stabilizer's performance most closely approximated that of the NACA 0015 and, thus, was indicated as such. Discussion with Bell indicated that early in the Huey's development, the decision was made to cover the tail rotor drive shaft and that the aerodynamic evolution of the vertical stabilizer was due to a desire to streamline that drive shaft cover.

E. CAMBER

Vertical stabilizer camber is necessary to unload the tail rotor during high speed flight thereby reducing tail rotor power requirements which otherwise begin to become prominent at that end of the flight envelope as they were at the hover end. Camber assumed prominence as a design variable with recent aircraft development. Both the AH-64 and the UH-60 have highly cambered vertical stabilizers.

Hughes' selection of the NACA 4415 was based, largely, on the amount of camber that it could provide. Reference 14 provides an indication of the extent of camber. Initial models and prototypes were built with a variable aft portion, much like a rudder and in fact so termed by Hughes. Variation of the rudder deflection angle produced variable airfoil performance and was an integral part of the empennage evolution. [Ref 14] Reference 4 relates an interesting account of the constraints imposed upon engineering by management when the only prototype (of a total of 4) configured with a variable rudder was lost in an unfortunate mid-air collision.

Sikorsky selected an airfoil (the NACA 0021) with considerably less camber than the NACA 4415 for the UH-60. It also possessed a variable deflection rudder; an optimum deflection was decided upon during the testing phase. Production models of both aircraft have fixed rudders.

One of the earliest, and most extremely cambered, vertical stabilizers was that of the Bell, AH-1G, Cobra. The Cobra has a very high maximum velocity (for a helicopter), 200 knots, during high speed dives reflecting its role as a gunship designed for the Vietnam era. This was quite radical for a helicopter during the mid 1960's when the Cobra was developed. Directional control problems which were encountered in this flight regime were solved by highly

cambering the vertical stabilizer. It is interesting to note that the Cobra began life with a vertical stabilizer identical to that of the UH-1--utilization of a proven component.

F. ASPECT RATIO

Table I indicates that an aspect ratio between 1.7 and 3.0 can be expected for medium weight helicopters. Although it has a significant effect on performance, aspect ratio is probably not a significant design variable. It is dictated by other considerations. Minimizing weight is critical in the empennage. Therefore, the smallest structure still capable of supporting the tail rotor, drive shaft and gear box is desirable. Keeping the structure small also assists in keeping the blockage ratio minimal. Minimum height is also desirable for military helicopters. This stems from tactical visibility (detection by the enemy) and the fact that specifications for air transportability requirements may limit the overall height. Examination of available data reveals no helicopter in production today with a vertical stabilizer appreciably higher than the main rotor. Emphasis on dynamic considerations may place the tail rotor hub at the same height (or nearly so) as the main rotor. Empennage configuration and structural considerations of vertical stabilizer integration with the tail boom are additional factors which affect the aspect ratio.

G. NEW AIRCRAFT DEVELOPMENT PROBLEMS

The U.S. Army/Sikorsky UH-60A Blackhawk and the U.S. Army/Hughes AH-64 Apache, two of the most recently developed helicopters, both experienced extensive problems with the vertical stabilizer throughout their development. Army specifications for both aircraft required that in the event of complete loss of tail rotor thrust, the aircraft be capable of maintaining level flight with 20 degrees maximum sideslip angle at the speed for minimum power. This requirement necessitates a large vertical stabilizer (in conventional design) to provide sufficient yawing moment to balance main rotor torque and to overcome the natural instability of the fuselage. In both cases the preliminary designs indicated an ability to satisfy this requirement.

Additional design constraints were imposed by air transportability requirements. The aircraft was required to fit into a C-130 transport aircraft (this was the most critical requirement in this respect as C-5 and C-141 size restrictions are less stringent). This, of course, limited the overall vertical height. In addition, there were requirements related to the time necessary for the aircraft to be made ready to fly after landing, which in turn limited the extent to which the aircraft could be dismantled in conjunction with loading. [Refs. 1 and 4]

In the AH-64 development, two design changes occurred during development which seriously degraded the capability to satisfy the flight with zero tail rotor thrust requirement. Substitution of the Hellfire Missile System for the original TOW system resulted in greater weight and drag. Additionally, an increase in drag was realized from a change in design of the cockpit canopy from a curved canopy to a flat plate canopy. These increases in drag and weight were compensated for somewhat by an increase in the vertical stabilizer planform area from 27 to 32 square feet. This change notwithstanding, flight without tail rotor thrust was not possible. The problem could have been satisfied by one of two methods: (1) by enlarging the tail rotor, however, this increased the already large blockage ratio to an unacceptable level; or (2) by adding a ventral fin to the bottom of the tail; this proved unfeasible due to limited area under the tail boom and related to ground clearance requirements. [Ref. 4]

The UH-60 vertical stabilizer evolution grew from a desire to overcome a vertical stabilizer tail rotor blockage problem which,in testing, had proven to be considerably more significant than preliminary design and analysis indicated. The UH-60 has a tractor tail rotor which compounded the problem. Sikorsky determined that removal of the upper 75% of the deflected trailing edge rudder yielded a 40% to

50% reduction in tail rotor power requirement. This also significantly improved a rather large pedal migration between hover and maximum velocity which was of considerable concern to Sikorsky test pilots. However, accompanying these two improvements was the complete degradation of the ability to satisfy the flight with zero tail rotor thrust requirement. Sikorsky's attempted solution was a slotted vertical stabilizer. This concept showed outstanding aerodynamic promise initially, but ultimately revealed unforeseen and unacceptable structural stresses which with considerably increased costs eventually proved to be the concept's undoing. Sikorsky eventually acknowledged their inability to meet the flight with zero tail rotor thrust requirement.

The Army and the contractors reached the same decision in both cases. The requirement was relaxed to permit a descent with tail rotor thrust loss or if sufficient altitude was available to attain an airspeed of approximately 125 knots, continued flight was possible. One might question the rationale for such a stringent requirement in the first place. It is suspected that it grew out of the Vietnam experience in which many Army helicopters sustained combat damage to the tail rotor system (particularly the tail rotor drive shaft) from hostile ground fire. Future expectations to such an extent are quite reasonable.

However, there is also an opinion that the majority of conditions resulting in loss of tail rotor thrust occur in conjunction with takeoffs, landings and in the NOE environment at such low altitudes and airspeeds that no vertical stabilizer, regardless of size, could produce sufficient thrust to enable continued flight. [Ref. 14]

III. CONCEPTUAL DESIGN PROCEDURES

A. QUALITATIVE ANALYSIS

1. The objective of the conceptual design procedure presented herein is to cultivate a method whereby the physical parameters of vertical stabilizer design are developed, then integrated with performance parameters producing an overall effect on helicopter performance. Preeminent concern is the contribution to (or detraction from) tail rotor thrust which can be experienced with a lift/thrust producing vertical stabilizer design. Application of a vertical stabilizer design which augments tail rotor thrust enables power, which would otherwise have been consumed by the tail rotor, to become available for the main rotor. Or in the event of loss of tail rotor thrust, continued flight is possible with the vertical stabilizer providing the required anti-torque force.

Assumptions made throughout might well be criticized with respect to their validity. However, some justification is provided by the fact that this procedure was required to coalesce with the evolution of and to augment the Naval Postgraduate School Helicopter Design Course, AE 4306.

The initial decision required is to determine the velocity at which the tail rotor is to become completely unloaded; i.e. that point at which the lift/thrust produced by the vertical stabilizer will equal the main rotor torque. One might also choose to evaluate several designs over a range of velocities. In such case, generation of a table such as Table III is recommended.

2. Next, calculate the section lift coefficient, C_ℓ, using:

$$C_\ell = 2l/\rho V^2 S$$

where:

l = lift

ρ = air density

V = free stream velocity

S = vertical stabilizer planform area

It will be necessary to calculate the lift produced by the vertical stabilizer. This lift can be set equal to the tail rotor thrust since that is one of the design specifications. Then the lift can be found using the equation:

$$l = T_{TR} = P_{MR}/(l_T \times \Omega_{MR})$$

where:

T_{TR} = tail rotor torque

P_{MR} = total power, main rotor

Ω_{MR} = rotational velocity, main rotor

l_T = tail length

Also, determine the vertical stabilizer planform area, S, as a function of tail rotor solidity from Figure 7.

3. The next section involves the use of DATCOM 4.1.3.2-49 to determine the section lift curve slope. This section of DATCOM can be found in the course notes from AE 4501, Current Aerodynamic Analysis [Ref. 15]. It is recommended that this source be employed because the notes include a thorough explanation along with examples. DATCOM begins with a predetermined airfoil section, then obtains the incompressible 2-D section lift curve slope from experimental data. For the purpose of this procedure, a value of 2π is used. Aspect ratio is determined in the traditional method with a span equal to 20% of the tail length. This figure is somewhat interesting in the respect that it is both quite simplistic and uncannily accurate for helicopters currently in production and included in Table I. As discussed in Chapter II, attempts to develop a method to determine leading edge sweep angle proved fruitless to the extent that among the field of helicopters examined, there was not significant deviation from roughly 42 degrees. As Table I shows, the sweep angle at the half chord is consistently 3 to 4 degrees greater than the leading edge angle. Thus, 45 degrees was selected as a nominal half chord sweep angle for use with DATCOM.

4. The design procedure is now at a point where two of the four parameters in the lift equation, $C_\ell = C_{\ell,o} + C_{\ell,\alpha}\alpha$, are known. C_ℓ and $C_{\ell,\alpha}$ have been determined. One

must select a $C_{\ell,o}$ and an α which prove feasible. Feasibility is naturally governed by airfoil aerodynamic performance and structural considerations. Experience indicates that a value near 0.4 is a reasonable maximum for the zero angle of attack section lift coefficient; 17 degrees is the time honored limit for angle of attack. The example in the following section provides a quantitative indication of the relative tradeoffs between the two parameters. Qualitatively, the choice, as with any airfoil, lies between achieving desired performance through camber or angle of attack or a combination of both. Recent experience with the Blackhawk and Apache helicopters indicates that when vertical stabilizer lift or thrust production is treated as a design priority, a relatively high degree of both angle of attack and camber is necessitated. The Apache airfoil section, NACA 4415, has a $C_{\ell,o}$ of 0.4. As this amount of camber does not provide the necessary lift, an angle of attack contribution is required. This is provided by what is essentially a high lift device in the form of a trailing edge flap. See Figure 3. While quite elementary with respect to airfoil design, such is rather innovative in helicopter design.

The obvious alternative to attaining lift from a flap of some other form of a high lift producing device is to mount the stabilizer at a fixed angle of incidence to the

longitudinal axis of the helicopter, thus achieving the desired angle of attack. Bell utilizes this approach with their Model 222. This design employs a 2.5 degree angle of incidence in conjunction with the fascinating Clark Y airfoil. This comprises a very interesting deviation from the status quo of helicopter design. Relative merits of this design were not analyzed in the course of this writing. However, it should be pointed out that the 222 empennage is closely akin to the OH-58/Jetranger family as opposed to the UH-1 family in the respect that the tail rotor and gearbox assemblies are not mounted on the vertical stabilizer (as is the case with the UH-1 family), but are attached to the tail boom (as with the OH-58/Jetranger family). Recall that vertical stabilizer mounting adds considerable complexity to the empennage.

This conceptual design procedure draws on preliminary data and calculations which normally would have been conducted prior to embarking on vertical stabilizer design. Table II presents a sample helicopter with the design and performance parameters selected by attempting to employ mean values from the helicopters presented in Table I. Thus, a somewhat "generic" helicopter was created. This "generic" helicopter is actually quite reasonable; it meets all design criteria and specifications in accordance with Reference 16.

Basic helicopter performance calculations are a precept for this design procedure. HP-41 programs for performing necessary calculations are found in References 17 and 18. It is necessary to be cognizant of the parameters included in Tables II and III. Tail rotor solidity and tail length are also required.

B. DESIGN EXAMPLE

1. Velocity at which the tail rotor is to be completely unloaded: two velocities shall be used, 80 and 160 knots.

2. Section lift coefficient:

$C_\ell = 2l/\rho V^2 S$

a. Calculate lift

$l = T_{TR} = P_{MR}/l_T \Omega_{MR}$

$T_{TR} = 619\ (550)/29\ (30) = 391$ lbf (V=80 kts)

$T_{TR} = 1070$ lbf (V=160 kts)

T_{TR} is tabulated in Table III

b. From Figure 7, S = 22 sq ft

c. $\rho = 0.0023769$ lbf sec/ft

Thus: $C_\ell = 0.830$ (V=80 kts)

$C_\ell = 0.566$ (V=160 kts)

3. Determine section lift curve slope: use DATCOM 4.1.3.2-49 (AE 4501 Notes, p. DC-7)

where: AR= 1.53 (from: b=1/5; AR=b/S=1.53)

Λ_{LE}= 45 degrees

β = 1.0

κ = 1.0

Thus: $C_{\ell,\alpha}$ = 0.036/deg

4. Select a range of values for C and determine angles of attack, α,

for each $C_{\ell,o}$

$C_{\ell,o}$ = 0.0, 0.2, 0.3, 0.4

Use: $C_{\ell} = C_{\ell,o} + C_{\ell,\alpha}\alpha$

at V=80 kts, C_{ℓ} = 0.0830, $C_{\ell,\alpha}$ = 0.036

$C_{\ell,o}$ = 0.0 α = 23.3

$C_{\ell,o}$ = 0.2 α = 17.7

$C_{\ell,o}$ = 0.3 α = 14.9

$C_{\ell,o}$ = 0.4 α = 12.1

at V=160 kts, C_{ℓ} = 0.0566, $C_{\ell,\alpha}$ = 0.036

$C_{\ell,o}$ = 0.0 α = 15.9

$C_{\ell,o}$ = 0.2 α = 10.3

$C_{\ell,o}$ = 0.3 α = 7.5

$C_{\ell,o}$ = 0.4 α = 4.7

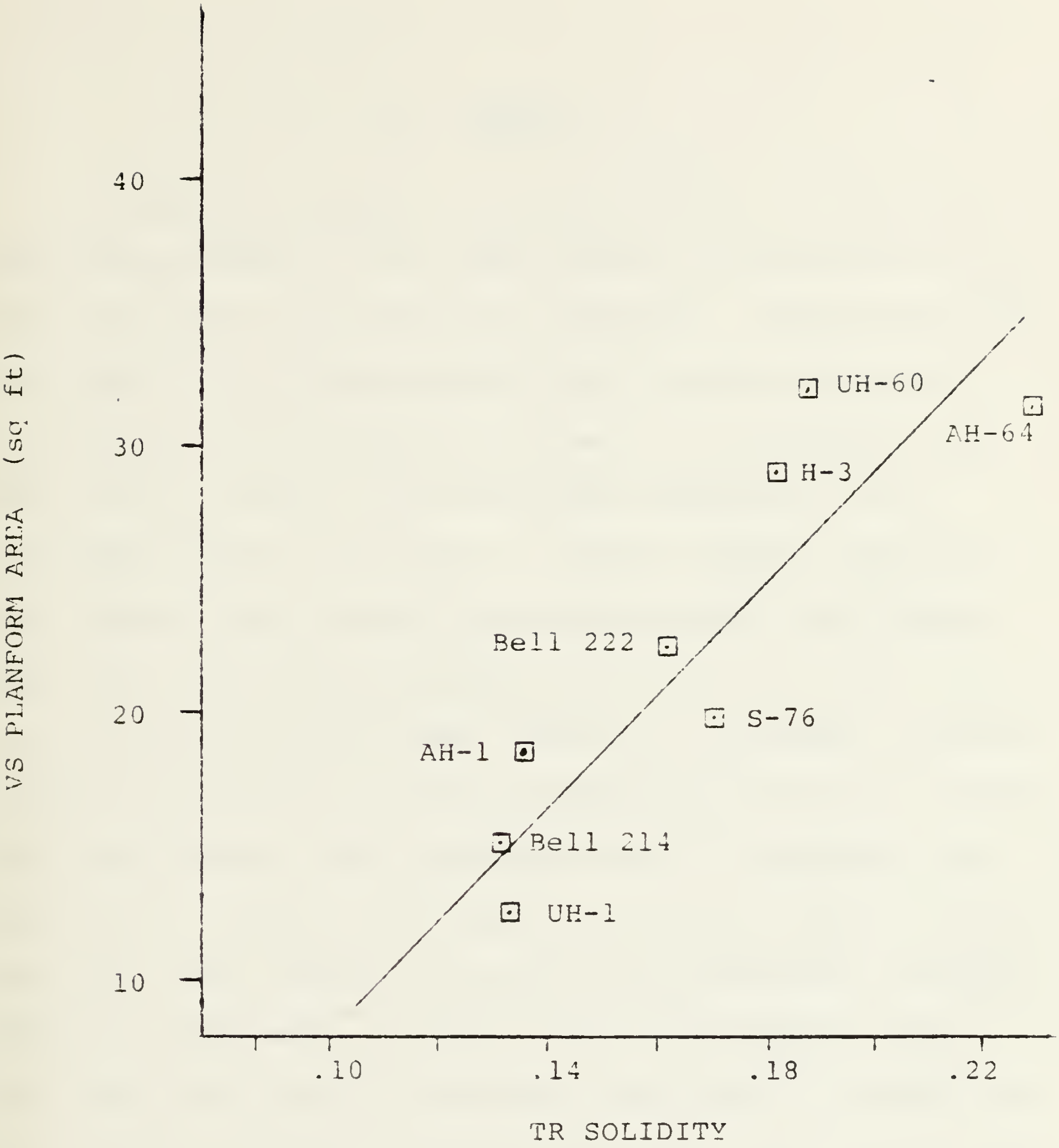


FIGURE 7 VS PLANFORM AREA AS A FUNCTION OF TR SOLIDITY

IV. RESULTS

In recent development, helicopter vertical stabilizer design considerations have been assuming increasing significance throughout the helicopter community. Exploration and development of an understanding and an appreciation for those design considerations have been the predominate concerns of this thesis. They have been analyzed in the traditional sense of airfoils: airfoil section, planform area, aspect ratio, leading edge sweep angles, and camber along with the interrelationship with the tail rotor. The vertical stabilizer has been treated in a somewhat singular approach as an entity, with the exception of the tail rotor interrelationship. This approach might be subjected to a question of validity with respect to the lack of consideration for a more thorough analysis of the empennage elements effects on each other and of the flow environment (main rotor wake and vortices) effects on the vertical stabilizer. This thesis intended to concentrate solely upon the vertical stabilizer based on the belief that an understanding of empennage design necessitated a preliminary exploration of design considerations for the various elements of the empennage (tail rotor, horizontal and vertical stabilizers) each separately.

The Naval Postgraduate School Helicopter Design Course, heretofore, had not dealt with vertical stabilizer design considerations. Thus, integration of such was deemed essential and, in fact, was largely responsible for precipitating this thesis. Chapter II presented a conceptual design procedure devised and employed by Sikorsky. While an excellent procedure, it did not ideally suit Naval Postgraduate School needs. Chapter III developed a conceptual design procedure which met those needs and integrated quite satisfactorily with the existing course. It was initially intended that the procedure be more detailed and involve making greater use of historical data and trends. While well intentioned and attempted, these efforts were frustrated. Significant correlations either did not exist between parameters which initially seemed quite plausible, or they exhibited no significant deviation between extremes, and, thus, provided too little decision making latitude. Attempts to correlate parameters such as main rotor height and vertical stabilizer span evidenced the former while gross weight vs. leading edge sweep angle evidenced the latter. See Table I. Good correlation was found between tail rotor solidity and planform area. See Figure 7.

One significant outcome of the work involved with this thesis is the extensive list of references and bibliography. The sources constitute a thorough compendium of the most

current available on the subject. References 1, 3, and 4 represent the most recently (February, 1983) completed efforts. The material included in the references and bibliography represents the historical evolution of the subject quite well. Undoubtedly, many undiscovered sources could augment and supplement those included herein, particularly NASA reports which contain valuable related material but may not deal exclusively with the subject.

Also of importance has been the identification of and development of a dialogue with the Applied Technology Laboratory of the U.S. Army's Aviation Research and Development Command as the focal point in this country for research in this subject area. Considerable resources have been dedicated to the establishment of a data base to document the results of design efforts and to propagate knowledge gained throughout future efforts. Indeed, the principal references used herein were a direct result of the application of those resources. They were prepared under contract to ATL. Results produced thus far have proven invaluable to the helicopter community and can be expected to continue providing such contributions.

V. CONCLUSIONS AND RECOMMENDATIONS

This thesis represents a highly successful effort to develop and present helicopter vertical stabilizer design considerations. Success notwithstanding, the imposed limitations and narrowed focus restricted the thesis such that it emerges somewhat limited and, thus, beckons for expansion. Limitations of medium weight and low tail configuration dictated a vertical stabilizer upon which the tail rotor assembly could be mounted. By convention, this would also necessitate an intermediate tail rotor gear box thereby further increasing empennage complexity. Deviation from this rather ultra conventional design (without transitioning to completely innovative concepts) to features such as a high tail boom, larger weight range considerations, canted tail rotor, and mounting the vertical stabilizer at an angle of incidence (Bell 222) would greatly increase the latitude available to the designer. Transition to innovative concepts would involve analysis of concepts such as the slotted vertical fin first proposed by Sikorsky and the Hughes NOTAR concept.

During analysis of the principal design tradeoff between the desirability of a large vertical stabilizer enhancing directional stability and providing flight with no tail

rotor thrust capability and the preference for a small vertical stabilizer to minimize tail rotor blockage effects, an idea emerged which warrants further analysis. Perhaps both demands could be satisfied with a vertical stabilizer with variable slats permitting operation in configurations optimizing either consideration depending upon the flight regime. Slats closed produces large area necessary for directional stability and no tail rotor thrust while opening the slats at a hover results in a small area and reduced blockage. The initially apparent drawback appears to be with respect to increasing complexity and weight in the empennage. This concern may prove to be overwhelming. Recall Mr. Ray Prouty's adamant insistence that utmost priority in design considerations be granted that aspect of empennage design. Nevertheless, ideas such as this, which do merit further analysis, are the sources of design innovation and change.

This thesis dealt with the vertical stabilizer as a singular entity with adequate subject treatment demanding some consideration of the tail rotor interrelationship. However, this subject demands expansion in scope and amplification in depth in future work. A logical follow on would then be inclusion of the horizontal stabilizer which was completely excluded from this work. Next progression could then be to the empennage with analysis of the tail rotor,

horizontal and vertical stabilizer with respect to their effects upon each other and also the synergism of those empennage elements. They certainly function synergistically, thus, their academic treatment as such is warranted. One would be well advised, however, to be aware of the complexity and difficulty of such a venture. The merest consideration conjures a matrix of such proportion to intimidate the most stalwart. The three elements affect each other and are, in turn, each affected by main rotor and fuselage flow and vortices, and ground vortices.

The outcome of the analysis of historical data and trends included herein is substantially less than satisfying and demands further attention. The data base should be expanded to include additional helicopters. Time requirements necessary to contact and solicit response from manufacturers cannot be underestimated. Searching for such information as included in Table I in sources other than directly from industry sources is fruitless. Further analysis of existing parameters and expansion of Table I to include additional parameters is necessary. Such analysis, if productive, should lead to an expanded, more dynamic conceptual design procedure providing increased latitude to the user and enhancing the results.

TABLE I--VERTICAL STABILIZER DATA

A/C	Gross Wt (lbs)	Λ_{LE} (deg)	$\Lambda_{1/2C}$ (deg)	σ_{TR}	AR	S (sq ft)	b (ft)	$\overline{C}$ (ft)	C_{TIP} (ft)	C_{ROOT} (ft)	Vol (cu ft)
UH-1H	9500	44	48	.134	1.74	11.2	4.42	2.34	1.74	2.95	385
UH-1N	10500	44	48	.136	1.74	11.2	4.42	2.39	1.74	2.95	
AH-1G/Q	9500	40.3	42	.136	1.54	18.5	5.33	2.52	0.78	2.78	455
AH-1S	10000	40.3	44	.136	1.54	18.5	5.33	2.69	1.74	3.30	500
UH-60A	20250	45	48	.188	1.92	32.3	7.86	3.32	2.83	3.75	980
AH-64	14660	28		.230	2.85	31.1	9.42		2.93	3.67	1080
S-76	9200	51		.172	1.73	19.7	5.83		2.42	4.35	550
SH-3H	19300	45		.183		29.0					1075
Bell 222	7850	57		.163		22.5					555
Bell 214	13800	45	49	.133	1.21	14.7	4.22	2.86	2.34	3.47	415
AH-1T	14000	40	44	.133	1.61	13.5	4.67	2.86	2.34	3.47	467
214 ST	17500	45	49	.133	1.55	12.0	4.31	2.34	1.56	2.43	

TABLE II

GENERIC HELICOPTER

		Main Rotor	Tail Rotor
Flat Plate Area (FPA-FF)	26		
Chord (C)		1.4	1.0
Radius (R)		24.5	3.75
No. blades (b)		4	2
$C_{d,o}$		0.01	0.01
Rotational Velocity (RV)		30	120
Wt	12500		

TABLE III

PERFORMANCE CALCULATIONS

V	P_{MR}	P_{TR}	P_{ACFT}	T_{TR}	C_{ℓ}
0	1165	95	1260	736	---
20	1013	71	1084	640	22
40	784	37	821	500	4.2
60	695	24	719	439	1.6
80	619	18	637	391	0.830
100	823	23	846	520	0.705
120	1017	29	1046	643	0.605
140	1304	38	1342	824	0.570
160	1692	54	1746	1070	0.566

LIST OF REFERENCES

1. U.S. Army Applied Technology Laboratory, USAAVRADCOM TR 82-D-22, Development of the UH-60A Directional Control System, Sikorsky, p. 33-42, May 1983.

2. Prouty, R. W., "Aerodynamics", Rotor and Wing International, p. 18-20, December 1982.

3. U.S. Army Applied Technology Laboratory, USAAVRADCOM Draft Report, Investigation of Operational and Design Factors Resulting from Main Rotor and Tail Rotor Interactions, by P. F. Sheridan, E. Hanker, and B. B. Blake, Boeing-Vertol, November 1982.

4. U.S. Army Applied Technology Laboratory, USAAVRADCOM TR 82-D-22, Development of the Empennage Configuration of the YAH-64 Advanced Attack Helicopter, by R. W. Prouty, Hughes Helicopters, October 1982.

5. Smith, R. P., "Development of the UH-60A Directional Control System", USAATL Technical Position Paper, 12 November 1982.

6. U.S. Army Air Mobility Research and Development Laboratory, USAAMRDL Technical Report 73-99, Tail Rotor Design Guide, by W. Wiesner, Boeing-Vertol, p. 29-30, January 1974.

7. Royal Australian Air Force, Aircraft Research and Development Unit, Report No. ARDU-TI-721, Bell 206B-1 Directional Control in Low Airspeed Flight, by L. R. Ward, p. 14-15, May 1981.

8. NASA, USAAMRDL Report NASA-TM-X-3501, Tail Contribution to the Directional Aerodynamic Characteristics of a 1/6 Scale Model of the Rotor Systems Research Aircraft with a Tail Rotor, by R. E. Mineck, May 1977.

9. Prouty, R. W., Visit to the Naval Postgraduate School, December 1982.

10. Ministry of Technology, Aeronautical Research Council, R & M No. 3514, A Theory of the Aerodynamic Interference Between a Helicopter Blade and a Fuselage and Wing in Forward and Hovering Flight, by A. R. Bramwell, p. 28-29, June 1965.

11. Ellison, D. E. and Mattan, L., USAF Stability and Control DATCOM, McDonald Douglas Corp., Project No. 8219, Air Force Flight Dynamics Laboratory.

12. U.S. Army Aviation Systems Test Activity, USAASTA Project No. 71-18, Tail Rotor Performance and Translational Flight Handling Qualities Test, UH-1 Helicopter, by R. L. Finnestead, p. 12, January 1972.

13. Bell Helicopter Textron, Letter to the Naval Postgraduate School, Subject: "Airfoil Data", 15 February 1983.

14. Abbott, I. H. and Von Doenhoff, A. E., Theory of Wing Sections, Dover Publications Inc., New York, 1959.

15. Zucker, R. D., Current Aerodynamic Analysis Course Notes, p. DC-7, Naval Postgraduate School.

16. Kee, S. G., Guide for Conceptual Helicopter Design, M.S. Thesis, Naval Postgraduate School, 1983.

17. Fardink, P. J., Hand Held Programs for Preliminary Helicopter Design, M.S. Thesis, Naval Postgraduate School, 1983.

18. Layton, D. M., Helicopter Performance Programs for the HP-41, Naval Postgraduate, 1983.

BIBLIOGRAPHY

Ferrell, Kenneth R., U.S. Army Aviation Engineering Flight Activity Report Bibliography 1961-1981, USAAEFA Project No. 81-90, Edwards AFB, CA, 1982.

Gessow, Alfred and Meyers, Garry C., Aerodynamics of the Helicopter, Ungar, 1952.

Kisielowski, E., Perlmutter, A., and Tang, J., Stability and Control Handbook for Helicopters, USAAVLABS Technical Report 67-63, Fort Eustis, VA, 1967.

Layton, Donald M., Helicopter Performance, Naval Postgraduate School, 1980.

McCormick, Barnes W., Aerodynamics of V/STOL Flight, Academic Press, 1967.

Products Reference Data, Bell Helicopter Textron, 1977.

Sanders, George H., Dynamics of Helicopter Flight, Wiley, 1975.

Sawyrda, A., The Feasibility of Replacing a Helicopter Tail Rotor, Report No. CAL-BB-2584-5-1, Cornell University, 1968.

Smith, Robert P., OH-58A Vertical Fin/Aft Tail Boom Surface Pressure Measurements Program, Applied Technology Laboratory, Fort Eustis, VA 1982.

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